2009 Fermi Symposium
eConf Proceedings C091122, 2-5 November 2009

Effects of retro-lensing light curves near a black hole

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Abstract. We model the light-curves from radiation-driven clouds near an accreting black hole. Taking into account the multiple images due to strong gravitational lensing, we find that sharp spikes can significantly enhance the observed flux. Following our previous work (Horák & Karas 2006a,b) we assume that scattering of ambient light takes place in a cloud that is in radial motion under a combined influence of black hole gravity and the radiation field. The retro-lensed photons give rise to peaks in the observed signal that follow with a characteristic time lag after the direct-image photons. Duration of these features is very short and the predicted polarization varies abruptly on the time-scale comparable with the light-crossing time of the system – a signature of the photon orbit. We also consider the polarization properties of scattered light.

1. Introduction

Holz & Wheeler (2002) proposed that the electromagnetic signal from a source located *in front of* a black hole may be significantly enhanced by the influence of strong gravitational lensing. They called this to be a retro-lensing effect (see also De Paolis et al. 2004), and considered it in the context of a putative detection in the Solar system: a stellar-mass black hole illuminated by light from the Sun and returning the ring of light back towards the observer. Albeit a speculative set-up of the system, the effect can find its application also in other sources containing a radiation source close to the black hole horizon at (almost) perfect alignment with the direction towards observer.

Related problems of strong-gravity lensing have been investigated by various authors (e.g. Ohanian 1987; Virbhadra & Ellis 2000; Bozza 2002). Retro-lensing images are formed by photon rays that make 180 degrees turn just above the black hole photon circular orbit. Although the signal is usually weak in these images, favourable geometrical arrangements are possible. Even more importantly, photons of these higher-order images experience a characteristic time delay (see Bozza & Mancini 2004; Čadež & Kostić 2005), and this could help to reveal the signatures of strong gravitational field in the system which may show up due to light signal making a complete turn around the black hole (Bursa et al. 2007; Fukumura et al. 2008, 2009).

Here we would like to stress a point, originally proposed in Horák & Karas (2006a), that characterising time delays together with the help of polarization information could constrain the model parameters to greater confidence than what is possible with only photometric light-curves. Furthermore, if the source of light is in a rapid fall towards the black hole then the retro-lensing signal become *enhanced* with respect to the primary signal, thereby emphasising the

importance of the indirect images that are a specific kind of signature of the a black hole horizon.

In fact, all higher-order images suffer from the attenuating influence of the light bending that reduces their luminosity, unless a special geometrical alignment of the source and the observer occurs and favours the opposite effect of magnification in a caustic. This can be quantified by the gain factor which determines the ratio of fluxes received in retro-lensed and direct images.

2. Light intensity and polarization

Horák & Karas (2006b) we considered a cloud of particles moving through the radiation field of a standard thin accretion disc. Primary photons from the disc are scattered by electrons in the cloud near the symmetry axis, they are beamed in the direction of the cloud motion and polarized by Thomson scattering.

The electron distribution is considered isotropic in the cloud comoving frame. We derived simple formulae for frequency-integrated Stokes parameters I, Q and U of the scattered radiation (Horák & Karas 2006a,b): $I = A[(1+\mathcal{A})(T^{tt}+T^{ZZ})+\mathcal{B}(T^{tt}-3T^{ZZ})-2\mathcal{A}T^{tZ}]$, $Q = A\left(T^{YY} - T^{XX}\right)$, $U = -2\,A\,T^{XY}$, where $\mathcal{A} \equiv \frac{4}{3}\,\langle\gamma_{\rm e}^2\beta_{\rm e}^2\rangle$, $\mathcal{B} \equiv 1 - \bar{\sigma}$, where $\bar{\sigma} \equiv \langle\beta_{\rm e}^{-1}\gamma_{\rm e}^{-2}\ln[\gamma_{\rm e}(1+\beta_{\rm e})]\rangle$; $\beta_{\rm e}$, $\gamma_{\rm e}$ are velocity and the Lorentz factor corresponding to an individual electron, while the angle brackets denote the averaging over the particle distribution in the cloud comoving frame (see Horák & Karas 2006b for notation and details of the calculation).

The Stokes parameters are evaluated in the polarization frame comoving with the cloud (one basis vector is pointed along the direction of the scattered radiation, while the other two basis vectors are perpendicular to it and to each other). The incident unpolarized radiation comes into the formulae as components of the stress-energy tensor $T^{\alpha\beta}$. The resulting polarization is linear, and so the fourth Stokes parameter V vanishes.

Total four-force f^{α} acting on the cloud is a superposition of the radiation and inertial terms. The cloud motion is solved in the spacetime of Schwarzschild black hole (radius $r_{\rm s}$). The radiation field influences the bulk motion of the cloud as well as the local electron distribution in the cloud frame. We find two critical velocities at which the polarization vector changes its orientation between transversal and longitudinal one.

determining the temporal evolution of observed intensity and polarization we consider the first three images of the observed radiation – the direct one and two retro-lensed images. The latter are formed by rays making a turn around the black hole. For small inclination angles these images take the form of Einstein arcs.

The retro-lensed photons give rise to peaks in the observed signal occurring with a characteristic mutual time lag after the direct-image photons. Duration of these features is very short and comparable to the light crossing time. They typically contribute about 10 percent of the scattered flux at most, but this result can be quite different for matter infalling on to the star. In that case the scattered photons are boosted in the downward direction and a considerable amount of light is directed on to the photon orbit. As a result, the retro-lensed

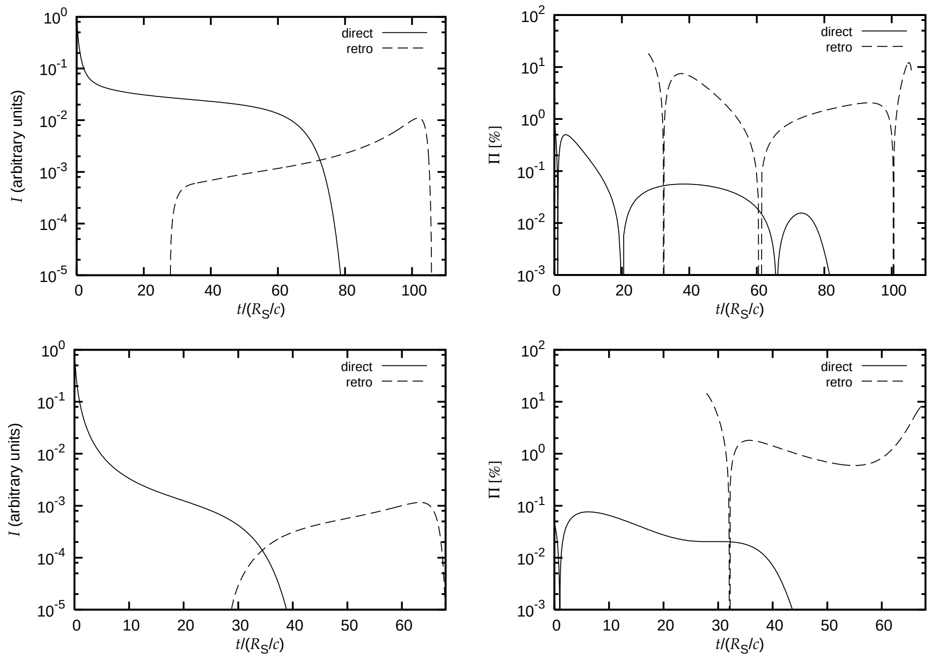

Fig. 1–Comparison of two typical cases with the identical initial conditions except for the cloud temperature: a cold cloud (upper panels, versus a warm cloud (lower panels, the electron Lorentz factor is 3 at start). Examples are shown of intensity (left panels) and polarization (middle panels) light-curves. Contributions of the retro-lensing images have been summed together (dashed line); they are clearly distinguished from the signal produced by the direct-image photons (solid line). Polarization vanishes at the moment when the cloud crosses one of the curves $\beta_1(\xi)$, $\beta_2(\xi)$. The view angle was $i = 5$ deg in both cases (figure adapted from Horák & Karas 2006b).

images become much more pronounced and they cause a brief flash of light, as illustrated in figure 1.

Conclusions

Although we described here a very simplistic model, our calculation is self-consistent in the sense that the motion of the gaseous blob and of the illuminating as well as scattered photons can be mutually interconnected. This interaction gives rise to the resulting lightcurves and also the predicted polarization at the observer.

We concentrated ourselves on gravitational effects and compared the flux intensities and the polarization magnitudes of direct and retro-lensing images. We noticed the mutual delay between the peaks of the observed signal, formed by photons of different orders. The detected time delays are expected to be approximately the light circle time near the photon orbit. This value is characteristic to the effect and it is proportional to the black hole mass.

We acknowledge the Czech-US collaboration project No. ME09036.

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